A Feasibility Study on the Predictive Emission Monitoring System Applied to the Hsinta Power Plant of Taiwan Power Company


To link to this article: https://doi.org/10.1080/10473289.2003.10466241

Published online: 22 Feb 2012.
A Feasibility Study on the Predictive Emission Monitoring System Applied to the Hsinta Power Plant of Taiwan Power Company

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ABSTRACT
The continuous emission monitoring system (CEMS) can monitor flue gas emissions continuously and instantaneously. However, it has the disadvantages of enormous cost, easily producing errors in sampling periods of bad weather, lagging response in variable ambient environments, and missing data in daily zero and span tests and maintenance. The concept of a predictive emission monitoring system (PEMS) is to use the operating parameters of combustion equipment through thermodynamic or statistical methods to construct a mathematic model that can predict emissions by a computer program. The goal of this study is to set up a PEMS in a gas-fired combined cycle power generation unit at the Hsinta station of Taiwan Power Co. The emissions to be monitored include nitrogen oxides (NOx) and oxygen (O2) in flue gas. The major variables of the predictive model were determined based on the combustion theory. The data of these variables then were analyzed to establish a regression model. From the regression results, the influences of these variables are discussed and the predicted values are compared with the CEMS data for accuracy. In addition, according to the cost information, the capital and operation and maintenance costs for a PEMS can be much lower than those for a CEMS.

INTRODUCTION
For the improvement of air quality, the Taiwan Environmental Protection Agency (TEPA) compels major stationary emission sources to install the continuous emission monitoring system (CEMS). The CEMS can monitor flue gas emissions continuously and instantaneously; therefore, the TEPA staff and the operator will know the amount of emissions and the operating situation of air pollution control devices. Moreover, the data from the CEMS also can be employed to calculate the air pollution fee and to be the database for emission reduction.

The operating experiences of the CEMS in Taiwan and other countries show that the cost of the CEMS is enormous. The capital cost of a complete CEMS is more than (U.S.)$100,000. Before commercial operation, several auditing tests must be conducted on a CEMS for it to be certified. Passing several auditing test routines, including the relative accuracy test audit (RATA), the relative accuracy audit (RAA), the cylindrical gas audit (CGA), and so on, to insure the accuracy of data, also costs plenty of money. Additionally, the CEMS has the disadvantages of easily producing errors in sampling periods of bad weather, lagging response in variable ambient environments, and missing data in daily zero and span tests and maintenance.

For some emission sources, the operating conditions are very stable. The concentration of nitrogen oxides (NOx) is usually related to the combustion condition. Therefore, emissions might be estimated from the air-fuel ratio and temperature. Because the sensors of these parameters have been installed in most emission sources, the predictive emission monitoring system (PEMS) can monitor emissions well with little installation cost.

The concept of a PEMS is to use the operating parameters of combustion equipment through thermodynamic or statistical methods to construct a mathematic model.
that can predict emissions by a computer program. The major components of a PEMS include:

1. ambient environmental parameter sensors,
2. burner (or turbine) control parameter sensors,
3. a computer system with predictive software (thermodynamics or statistical-based), and
4. a data acquisition system.

Generally speaking, the components of the CEMS include a sampling system, dilute gas analyzers (oxygen [O₂] or carbon dioxide [CO₂]), pollutant gas analyzers (sulfur dioxide [SO₂] and NOₓ), and a data acquisition system. However, the PEMS depends mainly on an information monitoring system. In fact, the PEMS is an information system. The difference between the CEMS and the PEMS is that the PEMS does not need actual pollutant monitoring analyzers. However, some sensors (e.g., temperature, pressure, flow rate), data transmitters, and record systems are still needed for a PEMS. If an existing CEMS is going to be transferred to a PEMS, many parts of the monitoring system still can be retained and operated.

In the early 1970s, the purpose of developing a NOₓ emission model was to save the developing cost of new types of burners. One of the earliest NOₓ emission models, a diffusion-limited mixed model, was developed by Hung in 1975. The research target of the model was a can-type gas turbine. Based on the Zeldovich mechanism, it was assumed that a plug flow reactor mixed completely and NOₓ formation was limited. The predicted results of the NOₓ model showed that the factors that impacted NOₓ emission were ambient humidity, operating condition, combustor geometry, types of fuel, and measuring accuracy.

There are two ways to develop emission models. One is based on thermodynamics; another is based on statistic regression. Predictive models based on thermodynamics have some applications; for example, GE new gas turbine. Based on the Zeldovich mechanism, several states have accepted the PEMS as a primary or alternative monitoring system. This kind of PEMS model has been employed by major companies. For example, Pavilion Co. developed a software that has been applied on a 430-MW gas turbine at the Ferguson power plant of the Lower Colorado River Authority. Two hundred parameters were chosen first. After primary screening by combustion model experts, the parameter number was reduced to 60. After many screenings, the final NOₓ predictive model only had 13 parameters.

In the recent U.S. PEMS experience, an installed PEMS has to undergo a RATA test. If an installed PEMS passes the RATA test, the PEMS will be certified by the authority. However, if the PEMS does not pass the RATA test, the model has to be rebuilt until it does pass the RATA test. Before 1994, 36 PEMS had been installed at small sites in the United States. Among them, 16 PEMS had passed the RATA test. Recently, EPA Regions VIII, IX, and X, and several states have accepted the PEMS as a primary or alternative monitoring system.

Besides small-scale PEMS, Pavilion Technologies, Callidus Technologies, and Aspen Technologies have many experiences with larger-scale PEMS in the United States. According to the papers presented by Callidus, they have installed more than 100 PEMS in the United States. In the South Coast Air Quality Management District (SCAQMD), because of the adoption of the stringent EPA quality assurance/quality control (QA/QC) regulation 40CFR75.40 (720 relative accuracy [RA] data), there are only two PEMS-installed plants. However, in Texas, where the TNRC adopted a self-ordained QA/QC regulation (only 30 RA data), there are many more PEMS applications. The research target of this study is a gas-fired combined cycle unit of Hsinta power station in Taiwan. A PEMS is developed to predict emissions of NOₓ and O₂.

**RESEARCH METHOD**

Based on the NOₓ-forming mechanism, thermal NOₓ will produce rapidly at high combustion temperatures. In addition, the Hsinta power station uses low nitrogen containing liquified natural gas; therefore, the major NOₓ-forming mechanism for the predictive model is thermal NOₓ. The major influent factors for thermal NOₓ formation are combustion temperature and excess air.
Combustion temperature \((T)\) and equivalence ratio \((\phi, \text{actual air-fuel ratio/stoichiometric air-fuel ratio})\) are, therefore, the key variances of the NO\(_x\) predictive model. \(\phi > 1\) indicates fuel-lean and \(\phi < 1\) indicates fuel-rich. Moreover, considering the influence of pressure on temperature in the gas turbine, pressure \((P)\) is also chosen as the variance.

As described previously, the NO\(_x\) predictive model can be written as

\[
\text{NO}_x = k_1 T^\alpha P^\beta \phi^\gamma
\]

(1)

where \(k_1, \alpha, \beta,\) and \(\gamma\) are constant coefficients. Because the stoichiometric air-fuel ratio is a constant, the equivalence ratio \((\phi)\) can be replaced by a real air-fuel ratio \((\lambda)\). Hence, the NO\(_x\) predictive model can be rewritten as eq 2:

\[
\text{NO}_x = k_1 T^\alpha P^\beta \phi^\gamma
\]

(2)

where \(\gamma_1\) is a constant coefficient.

Similarly, O\(_2\) concentration is related to fuel consumption and the amount of NO\(_x\) formation. Hence, the O\(_2\) predictive model also can be written as eq 3:

\[
\text{O}_2 = k_2 T^\mu P^\nu \phi^\xi
\]

(3)

where \(k_2, \mu, \nu,\) and \(\xi\) are constant coefficients. The multiple regression analysis of independent variances can be employed to find out those constant coefficients in eqs 2 and 3.

Because the PEMS is a regression model, data collection is an important step. The collected data are from two parts. One part is NO\(_x\) and O\(_2\) data from the CEMS; another is the operating parameter from the combined cycle. For convenience and accuracy, this study used the statistical software SAS to conduct the model regression.

The total capacity of each combined-cycle gas turbine (CCGT) in the Hsinta power plant is 440 MW. This CCGT made by Siemens includes three gas turbines (90 MW), one heat recovery steam generator (HRSG; 170 MW), and one steam turbine. The PEMS is set up in a Wintel-based personal computer (PC). The specifications of this PC are Pentium II 350, 128 MB RAM, and 8.4-GB hard disk, and the operating system is Microsoft Windows 98.

RESULTS AND DISCUSSION

Depending on the collected data quality, the development of the PEMS model can be divided into three stages: (1) model by daily average data, (2) modified variances and model by per-minute data, and (3) model by amendment of data calculation.

First-Stage Model

The first stage was the preliminary trial, so the regression model only employed 1-month daily average data to check the validity of selected variances. Thus, the first stage model is obtained as

\[
\text{NO}_x = 4.496 \times 10^{-48} T^{15.425} P^{-0.355} \text{O}_2^{6.015}
\]

(4)

where NO\(_x\) is the NO\(_x\) concentration (ppm); \(T\) is the average temperature of the gas turbine outlet (°C); \(P\) is the average pressure differential of the combustion chamber (kPa); and \(\text{O}_2\) is the oxygen content (%). The obtained formula gives \(R^2 = 0.60875\) and \(F\) value = 6.74. The significance of regression is evaluated using the \(F\) test. If the estimated (empirical) value exceeds the threshold value (which corresponds to the 95% cumulative probability distribution), then the effect of all factors combined is significant. (The threshold values for probability \(P\) can be found in statistic textbooks.) To check the accuracy of this predictive model, 72-hr independent data were fitted in this model. The comparisons of predicted values and measured values for NO\(_x\) are shown in Figure 1. The figure shows that the predicted NO\(_x\) value accurately falls around the measured value and does not deflect too far. The maximum difference between the predicted value and the measured value is within 5 ppm. However, the line of the predicted value is smoother, and it cannot predict oscillation. The reason could be that the data are insufficient and variances need to be modified.

The comparisons of O\(_2\) values are shown in Figure 2. The predicted value also accurately falls around the measured value, and the maximum difference between the predicted value and the measured value is within 1%.
From the results of the preliminary trial, selected variances are valid, but further modification is necessary for precise prediction.

Second-Stage Model

In the second stage, origin variances were modified, and new variances—ambient temperature (inlet temperature of compressor), airflow rate (aperture) of the air damper, and combustion chamber temperature (temperature of gas turbine outlet)—were added. By employing modified variances and 1-month per-minute data, the second model is obtained as

$$\text{NO}_x = 8.680 \times 10^{-2}T_o^{-0.255}P^{-0.102}Q_I^{-0.886}T_a^{0.116}I^{2.088}$$

where \(\text{NO}_x\) is the \(\text{NO}_x\) concentration (ppm); \(T_o\) is the temperature of the gas turbine outlet (°C); \(P\) is the pressure of the combustion chamber (MPa); \(Q_I\) is the fuel flow rate (m³/hr); \(T_a\) is the inlet temperature of the compressor (°C); and \(I\) is the aperture of the air damper (%). The obtained formula gives \(R^2 = 0.1263\), and \(F\) value = 933.59. Some 16-day independent per-minute data were fitted in this model. The comparisons of predicted values and measured values for \(\text{NO}_x\) are shown in Figure 3.

The \(O_2\) model also employed 1-month per-minute data, and the formula is obtained as

$$O_2 = 0.908T_o^{0.428}P^{0.792}Q_I^{0.034}T_a^{0.047}I^{-0.117}$$

The obtained formula gives \(F\) value = 7.67. Some 16-day independent data were then fitted in this model. The predicted \(O_2\) values and the corresponding CEMS values are shown in Figure 4. The \(F\) values of the parameters of the PEMS models for \(\text{NO}_x\) and \(O_2\) are shown in Table 1.

To meet the regulations of Taiwan, the predictive result of the PEMS is presented as an emission concentration. However, in the United States, the predictive result of the PEMS is presented as emission mass. This study also conducted a similar simulation, and the predictive results are shown in Figure 5, which shows that the trend of predicted values in emission mass are even closer to measured values.

Third-Stage Model

The third-stage model was based on the second-stage model, but the formation of some variances were
Employing 1-month per-minute data to conduct the regression, the NO\textsubscript{x} model is obtained as

\[
\text{NO}_x = 1.328 \times 10^{-9} T_o^{0.376} P^{-2.454} Q_f^{-0.078} T_a^{3.412} I^{0.040} \tag{7}
\]

where the definitions of variances are the same as in the second-stage model. The data of \(T_o, P, \) and \(T_a\) use average actual combined cycle data as in the second-stage model. However, \(Q_f\) and \(I\) use the summation data of three gas turbines. The formula gives \(R^2 = 0.356\) and \(F\) value = 3966. Some 16-day independent data were then fitted in this model. The predicted NO\textsubscript{x} values and the corresponding CEMS values are shown in Figure 6.

Similarly, the \(O_2\) model is obtained as

\[
\text{O}_2 = 13.992 T_o^{-0.009} P^{-0.013} Q_f^{-0.002} T_a^{0.014} I^{-0.001} \tag{8}
\]

The formula gives \(R^2 = 0.266\) and \(F\) value = 2610. Some 16-day independent data were then fitted in this model. The predicted \(O_2\) values and the corresponding CEMS values are shown in Figure 7.

The \(F\) values of the variances of the PEMS models for \(\text{NO}_x\) and \(O_2\) are shown in Table 2. The frequency of data acquisition in our PEMS was set as 1 min. However, the emission data submitted to the authorities are hourly average according to emission standards and CEMS-relevant regulations. Also, the hourly arithmetic mean values are averaged by four 15-min values. The 15-min and hourly variations in mass emission rate for \(\text{NO}_x\) are shown in Figures 8 and 9, respectively.

The comparative figures show that the predicted values of \(\text{NO}_x\) in mass closely match the values of CEMS. To

\[\text{Table 1. The } F\text{-values of variances of PEMS model for }\text{NO}_x\text{ and }O_2\text{ (stage 2).}\]

<table>
<thead>
<tr>
<th>(\text{NO}_x) (min)</th>
<th>(O_2) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F) Value</td>
<td>Prob &gt; (F)</td>
</tr>
<tr>
<td>Formula</td>
<td>933.59</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>407.24</td>
</tr>
<tr>
<td>Combustion pressure</td>
<td>3.43</td>
</tr>
<tr>
<td>Fuel flow</td>
<td>3620.55</td>
</tr>
<tr>
<td>Aperture</td>
<td>263.79</td>
</tr>
<tr>
<td>Combustion temperature</td>
<td>624.94</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.1263</td>
</tr>
</tbody>
</table>
check the accuracy and precision of this model, RA was conducted. The 15-min and hourly results of RA are shown, respectively, in Figures 10 and 11, which indicate that major RA values are within ±20%. Therefore, the third-stage model is basically acceptable.

COST ANALYSIS
According to the CEMS cost information collected by Chevron and Stone and Webster Engineering Corporation, the initial direct cost of a CEMS is (U.S.)$195,000 and the initial indirect cost is (U.S.)$171,000. Hence, the total installing cost is (U.S.)$366,000. The yearly operating cost is (U.S.)$27,000. Compared with the initial direct cost of a complete CEMS, the initial direct cost of CEMS, which only contains NOx, O2, carbon monoxide (CO), and flow rate analyzers, is only (U.S.)$137,000.

According to the collected U.S. cost information, the initial cost of a PEMS has three ranges, which are (U.S.)$95,000–(U.S.)$120,000, (U.S.)$150,000–(U.S.)$300,000, and (U.S.)$300,000–(U.S.)$400,000. The median of this cost data is ~ (U.S.)$150,000. Compared with (U.S.)$366,000, the initial cost of the PEMS is approximately half of the CEMS. In general, the major cost savings for the PEMS is the subsequent maintenance cost. In long-term estimation, the PEMS can significantly save costs.

In Taiwan’s experience, according to the CEMS cost information provided by the Hsinta power plant of Taiwan Power Co., the initial direct cost of a CEMS is (U.S.)$133,000 and the initial indirect cost is (U.S.)$62,000. Therefore, the total installing cost is (U.S.)$195,000. The yearly operating cost is (U.S.)$22,000. Compared with the initial direct cost of a complete CEMS in Taiwan, the initial direct cost of a CEMS, which only contains NOx, O2, CO, and flow rate analyzers, is just (U.S.)$96,000.

Table 2. The F-values of variances of PEMS model for NOx and O2 (stage 3).

<table>
<thead>
<tr>
<th></th>
<th>NOx (min)</th>
<th></th>
<th>O2 (min)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F Value</td>
<td>Prob &gt; F</td>
<td>F Value</td>
<td>Prob &gt; F</td>
</tr>
<tr>
<td>Formula</td>
<td>3965.97</td>
<td>0.0001</td>
<td>2609.78</td>
<td>0.0001</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>2206.33</td>
<td>0.0001</td>
<td>1756.83</td>
<td>0.0001</td>
</tr>
<tr>
<td>Combustion pressure</td>
<td>4056.5</td>
<td>0.0001</td>
<td>168.25</td>
<td>0.0001</td>
</tr>
<tr>
<td>Fuel flow</td>
<td>115.9</td>
<td>0.0001</td>
<td>115.81</td>
<td>0.0001</td>
</tr>
<tr>
<td>Aperture</td>
<td>4546.29</td>
<td>0.0001</td>
<td>310.89</td>
<td>0.0001</td>
</tr>
<tr>
<td>Combustion temperature</td>
<td>3130.75</td>
<td>0.0001</td>
<td>109.29</td>
<td>0.0001</td>
</tr>
<tr>
<td>R²</td>
<td>0.3556</td>
<td>0.2664</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Three PEMS were studied at Hsinta power plant. The average initial cost of a PEMS was ~(U.S.)$68,000 and the estimated yearly operating cost was (U.S.)$10,000. The cost information collected showed that the PEMS are more cost-effective than are the CEMS. The initial cost comparisons of the CEMS and the PEMS are shown in Table 3.

**CONCLUSIONS**

The developing process of the predictive model shows that it has improved accuracy after modification. Also, data quality is an important factor for the regression model. The analysis of model variances show that fuel flow rate and combustion chamber temperature are major impact variances for NOx formation, which agrees with NOx formation theory. The predicted values of the third-stage PEMS model have the best agreement with the CEMS values. Moreover, prediction of emission mass has higher accuracy, and RA is in the acceptable range. However, this work only studied a model for a combined-cycle unit; further tests are necessary to prove that the acquired PEMS model is proper for the different power stations.

**REFERENCES**


**ACKNOWLEDGMENTS**

This study was funded by Taiwan Power Co. Assistance from the staff of Hsinta power plant is gratefully acknowledged.

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**Figure 11.** RA of PEMS and CEMS hourly averages for NOx.

**Table 3.** Comparisons of CEMS and PEMS in initial cost.

<table>
<thead>
<tr>
<th></th>
<th>United States (U.S.$)</th>
<th>Taiwan (U.S.$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEMS</td>
<td>150,000</td>
<td>68,000</td>
</tr>
<tr>
<td>CEMS*</td>
<td>308,000</td>
<td>158,000</td>
</tr>
<tr>
<td>CEMS**</td>
<td>366,000</td>
<td>195,000</td>
</tr>
</tbody>
</table>

*The types of monitors include NOx, CO, O2, and flow rate analyzers.

**The types of monitors include SO2, NOx, CO, O2, opacity, and flow rate analyzers.**